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# Voltage Harmonics Mitigation through Hybrid Active Power Filer

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## ABSTRACT

Fast dynamic response, high efficiency, low cost and small size of power electronic converters have exponentially increased their use in modern power system which resulted in harmonically distorted voltage and currents. Voltage harmonics mainly caused by current harmonics are more dangerous as performance and expected operating life of other power system equipment are affected by harmonically distorted supply voltage. Electronic filter circuits are used to improve system power quality by mitigating adverse effects of harmonics. Hybrid filters having advantages of both passive and active filters are preferred to resolve the problem of harmonics efficiently and avoiding any chance of resonance.

In this paper, a three phase three wire network is considered to supply an adjustable speed drive represented by a resistive load connected across a three phase bridge rectifier. Simulation of the considered system shows THD (Total Harmonic Distortion) of 18.91 and 7.61% in supply current and voltage respectively. A HAPF (Hybrid Active Power Filter) is proposed to reduce these THD values below 5% as recommended by IEEE Standard-519. P-Q theorem is used to calculate required parameters for proposed filter, which is implemented through hysteresis control. Simulation results confirm the effectiveness of the designed filter as THD for both current and voltage have reduced below allowable limit of 5%.

**Key Words:** Power electronics converters, Voltage Harmonics, Total Harmonic Distortion, Hybrid Active Power Filter.

## 1. INTRODUCTION

Power electronic converters offer numerous advantages like small size, low cost, fast dynamic response and ease of control resulting in their extensive use in modern power systems from generation to consumer loads [1]. Solar PV (Photovoltaic) cells generate DC (Direct Current) power, which is then regulated through a DC-DC converter and then inverted to AC (Alternating Current) for synchronization with existing grid. On the other hand HVDC (High Voltage Direct Current) transmission links are used for their improved

efficiency and ease in synchronizing different frequency systems. AC power is first converted into DC through rectifiers and later inverted back into AC through inverters. Numerous load applications require DC power for their operations. Computers, laptops, mobile chargers, LED lights, CFLs and adjustable speed drives are some of the examples of such loads. Modern concepts for DC Microgrids and low voltage DC distribution also use power electronic converters. Batteries for energy storage and UPS (Uninterruptable Power Supplies) also make use of power

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electronic converters. Another important application of these converters is process control systems in a plant or manufacturing industry [2]. Despite of several advantages and applications, power electronic converters have drawback of injecting harmonics in power system [3].

Harmonics have been a prime contributor to modern power quality issues, making it one of the highly focused research area for electrical engineers. Over the last few decades nonlinear loads have increased tremendously in power system [4]. Harmonic distortion is a phenomenon where presence of different harmonics changes sinusoidal waveform of voltage or current [5]. Concept of harmonics started from the early use of AC systems and transformers are considered as initial source because magnetizing of transformer core caused distortion in sinusoidal wave. Harmonic sources have behaviour similar to conventional current sources and therefore, are called current harmonics. Current harmonics gave birth to voltage harmonics as harmonically distorted currents interacting with system impedance cause voltage distortion. In addition to these, unbalanced system operation also produces voltage harmonics [5]. Voltage harmonics also have adverse impacts on other nonlinear loads and extent of harmful impacts depends upon the location of harmonic sources, power sources and affected linear load. Harmonic distortion in current and voltage reduce equipment life by affecting its insulation and system efficiency through increased harmonic current. It also will reduce stability and reliability. Therefore, harmonic mitigation techniques are employed to improve system performance and efficiency improvement.

THD is normal measuring index for a harmonically distorted waveform [6]. It is defined as ratio of the square root of sum of the squares of all harmonic components to the fundamental frequency component. THD for voltage is given by Equation (1):

$$\text{THD}_v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \quad (1)$$

Where  $V_1$  is fundamental frequency and  $V_2, V_3, V_4$  to  $V_n$  are its harmonics. Percentage THD is more commonly used to compare different systems. IEEE-519 Standard [7] for acceptable level of harmonics describes 5% of THD as a boundary and any value above it is considered unacceptable.

Load generated current harmonics should either by conducted to ground or prevented from entering into other components [3]. Electronic filters are the circuits used for harmonic mitigation [6]. Passive and active filters have comparative merits and demerits. Selection of any filter circuit is based on designer choice by considering the constraints of cost and complexity. Hybrid active filter utilizes advantages of both active and passive filters thus providing a suitable solution while avoiding the drawbacks such as resonance [4,8].

Gupta, et. al. [9] compared shunt active filter and shunt hybrid filter for harmonic mitigation to inverter fed nonlinear load. Hybrid filters showed better performance for rejection of harmonics. Passive components were selected to mitigate 5<sup>th</sup> and 7<sup>th</sup> harmonics whereas active filter mitigates higher order harmonics. Tin, et. al, [10] compared passive, active and hybrid active filters for inverter fed load. They concluded that combination of passive and active filters is best suited to mitigate harmonics. Busarello, et. al. [11] proposed shunt hybrid filter for voltage source inverter. Proposed filter was controlled through d-q transformation and frequency selective filter technique. Akagi and Isozaki [12] designed a hybrid active filter for mitigating the source side harmonic currents of a three-phase 12-pulse diode rectifier used as the front end of a medium-voltage high-power motor drive. Proposed filter successfully overcome required harmonic mitigation. They also stated that a 6-pulse rectifier will produce higher harmonics. Joshi and Bohra [13] analyzed single phase domestic loads for harmonics and proposed hybrid active filter for mitigation of harmonics. Gonzatti, et. al. [14] stated that diode rectifiers with DC capacitors behaves like a harmonic voltage source. Shunt active filters normally used with current source type nonlinear loads

fail to properly mitigate generated harmonics. They suggested to use hybrid power filter technique for such nonlinear loads. Srivatsav, et. al. [15] compared series and parallel schemes for hybrid filters for three phase three wire system. They concluded that shunt hybrid filters performs better than series filters. Rehmani, et. al. [16] proposed shunt hybrid filter combined with TCR (Thyristor-Controlled Reactor) for harmonic mitigation and reactive power compensation. LC passive filter for 5<sup>th</sup> harmonic filter along with small active filters are combined for harmonic mitigation. TCR was controlled by PI (Proportional-Integral) controller using a lookup. APFs were controlled by two loop controller. Proposed filtering technique mitigates generated harmonics but cost and control complexity are concerns for such scheme for use in distribution systems. Kumar, et. al. [17] used hysteresis controlled active power filter for harmonic mitigation in three phase four wire system. Nonlinear load is represented by diode rectifier and resistive load. This technique requires large size of active power filter which is not economically feasible. Chaudhari and Tapan [18] compared control strategies for three phase three wire shunt hybrid filters. They suggested that hysteresis current control scheme based on P-Q theory is robust and easy to implement for PWM (Pulse Width Modulation) generation for switching active power filters.

In this paper, harmonics injected by a six pulse bridge rectifier fed load are observed using MATLAB/Simulink® software. HAPF is designed based on harmonic distortion observed through model simulation. Harmonic currents observed are used to design a HAPF using P-Q theorem. Designed HAPF is connected to model and simulated to verify filter effectiveness as THD of both source voltage and current are reduced below the acceptable level of 5%. Filter response is also obtained for reduced loads to check suitability of proposed HAPF.

The rest of paper is drafted as follows: In section 2 of the paper, harmonic filters are discussed where passive and active filters are compared. Section 3 describes the

considered network and its harmonics whereas results with designed filter are given in section 4. Section 5 concludes that designed HAPF effectively mitigates the harmonics injected by six pulse bridge rectifier and resistive load.

## 2. HARMONIC FILTERS

Harmonic mitigation refers to directing harmonics to ground or stopping those from penetrating into other system components. Electronic circuits designed to mitigate harmonics at their generation point are called electronic filters and are important to ensure satisfactory operation of other components of the system. Harmonic filters are based on impedance of the filtering equipment like resistor, inductor and capacitor. Reactance offered by an inductor ( $X_L$ ) and capacitor ( $X_C$ ) are dependent on signal frequency as given in Equations (2-3):

$$X_L = 2\pi fL \quad (2)$$

$$X_C = \frac{1}{2\pi fC} \quad (3)$$

Resistor, inductor and capacitor are passive components and filters designed with only these components are therefore termed as passive filters. Reactance of both inductor and capacitor are dependent on frequency and therefore any combination of RC, LC and RLC is used to allow or reject different frequency ranges. Actual technical and economic approach for harmonic suppression is through the use of passive filters [4] as they are simple, cost effective and robust but have drawbacks of significant size especially for low frequencies, additional losses, limited bandwidth around tuned frequency and difficulty in re-tuning [4]. Use of capacitor in passive filters provides power factor improvement. As filtering effectiveness of passive filters depends on the source impedance, accurately determined, passive filters may cause occasional parallel or series resonances [19]. Passive filters are preferred for high power applications.

Active filters use some of the active components like transistors and operational amplifiers in addition to passive components. Development in power electronics has also provided option of using active filters where a current out of phase with harmonic current is produced to cancel out effects of harmonic currents. Active filters have tendency to compensate harmonics distortion in both current and voltage. Active filters had controlled harmonic mitigation and can be easily retuned for changing system states caused by its expansion or alteration. Resonances caused by passive filtering components can be avoided by tuning the active filters. On the other hand they have drawbacks of high cost, harmonic stability and proper component sizing issues [5]. Relative merits and demerits of active and passive filters gave idea of using combination of both to maximize the benefits in harmonic mitigation at the most effective design. Such combination of active and passive filters is known as hybrid filters and provides cost effective, adjustable and robust harmonic mitigation technique [20]. The size of the filter used in hybrid filter is much smaller to that used only is active filter while eliminating chances of any resonance. Any harmonic filter design must achieve the optimal solution while satisfying many objectives;

generally, these objectives might be conflicting with each other. An important substitute for multi objective optimization is not to obtain the best solution but to obtain a good compromise solution [6].

### 3. SIMULATION MODEL

Fig. 1 shows a complete simulation diagram of system under analysis along with the complete setup of the system and proposed HAPF. Three phase AC source supplies a 8 $\phi$  resistive load connected through a three phase six pulse bridge rectifier. Load represents a typical adjustable speed drive. Voltage between each phase and ground for source is 220V with source and rectifier front end inductances of 1.06 and 2 mH respectively. DC bus capacitance is 4500  $\mu$ F. Fig. 2 shows three phase source current waveforms of the simulated network without proposed HAPF where highly distorted waveforms are clearly visible. FFT (Fast Fourier Transform) analysis showing harmonic spectrum of current is shown in Fig. 3 where a THD of 18.91% is observed. It can also be observed that 5<sup>th</sup> harmonic is most dominant followed by 7<sup>th</sup>. For number of pulses (p), expected harmonic orders are given by Equation (4).

$$h_n = k p \pm 1 \quad (4)$$

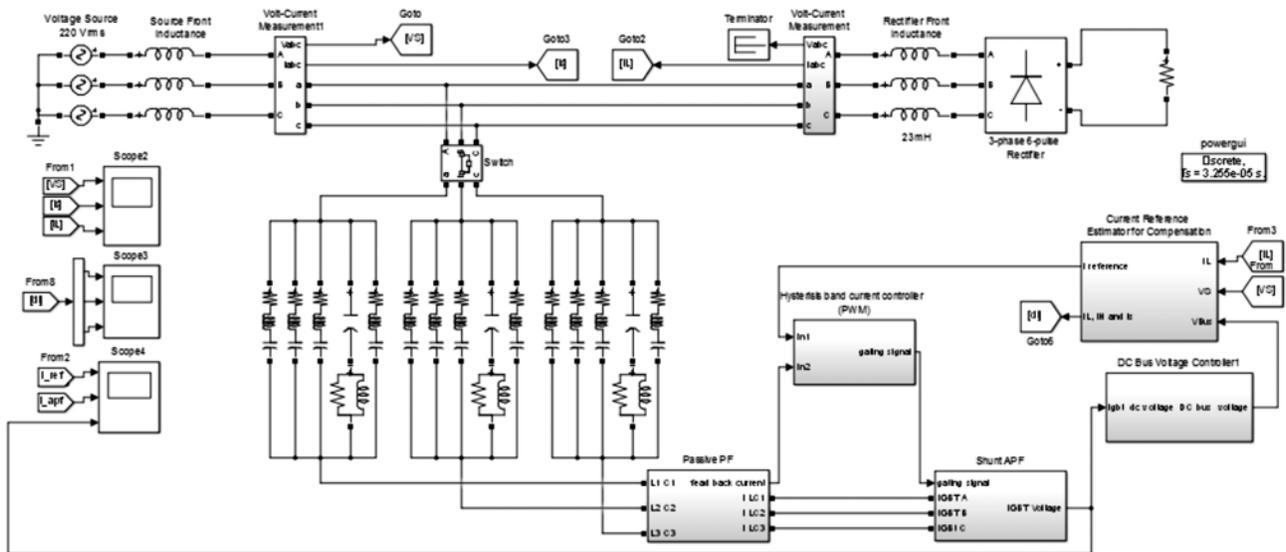


FIG. 1. SIMULATION DIAGRAM FOR MODEL CIRCUIT WITH COMPLETE HAPF

Where  $h_n$  is harmonic order and  $k$  is constant. For  $p=6$  and  $k=1$ , 5th and 7th harmonics will be present. For  $k=2$ , 11th and 13th harmonics will be present. Therefore, triplen harmonics 3rd, 9th, 15th and higher will be negligible, which is confirmed by FFT spectrum in Fig. 3.

Similarly for three phase source voltage, harmonically distorted waveform is shown in Fig. 4 and harmonic

spectrum in Fig. 5. THD for voltage is 7.69%. Again similar behavior for triplen, 5th and 7th harmonics is observable for voltage, confirming the current harmonics generated by six pulse rectifier as the resource for these harmonics. As THD for both voltage and current are greater than acceptable level of 5% given by IEEE standard 519, a harmonic filter technique is required to reduce harmonic distortion.

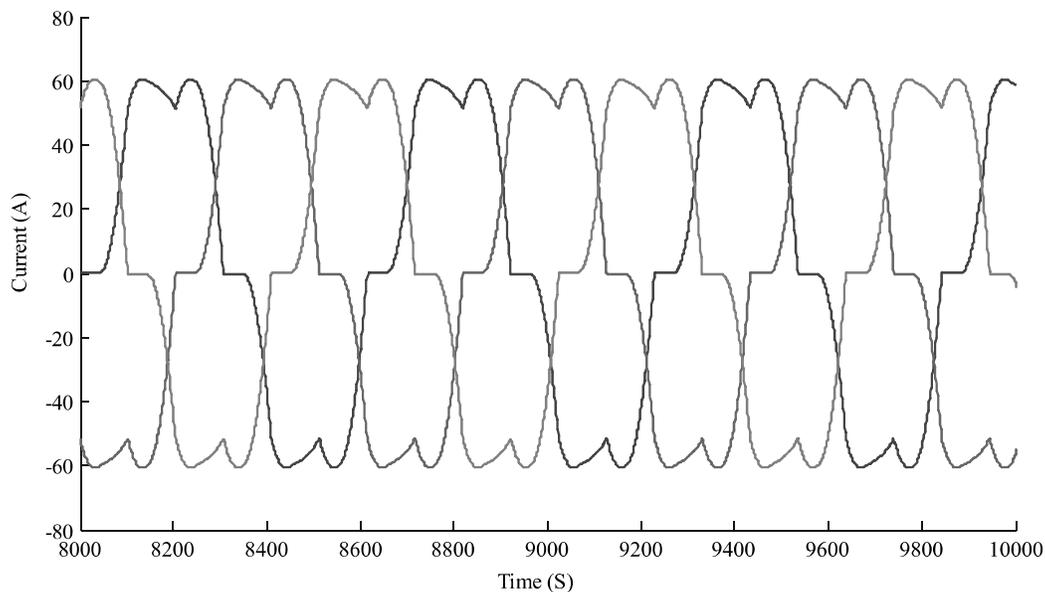


FIG. 2. SOURCE CURRENT WAVEFORM OF SIMULATED MODEL

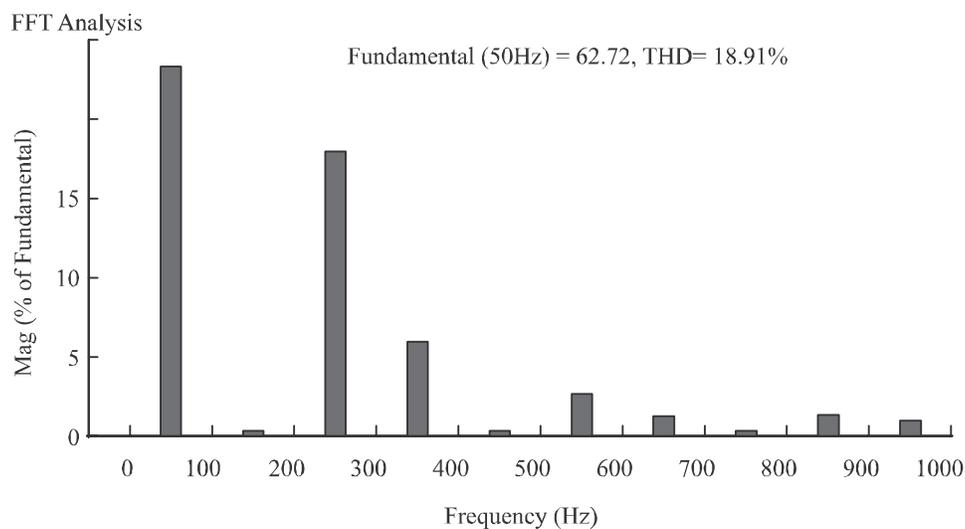


FIG. 3. HARMONIC SPECTRUM OF SOURCE CURRENT OF SIMULATION MODEL

#### 4. SIMULATION RESULTS

Harmonic spectrums shown in Fig. 3 and Fig. 5 clearly call for a filter design and HAPF is proposed. Reference current is calculated using PQ theorem in static  $\alpha$ -p frames so that a similar current out of phase can be inserted by HAPF. Table 1 shows parameters for R, L and C to compensate for different harmonics. Once parameters are selected, there

must be a controller to control the filter current injection to reduce harmonic distortion and restore DC bus voltage. Hysteresis control is employed here because of its simplicity and ease of implementation [20]. Fig. 6 shows that reference current is exactly tracked by current of the proposed HAPF, indicating suitable parameters for filter design.

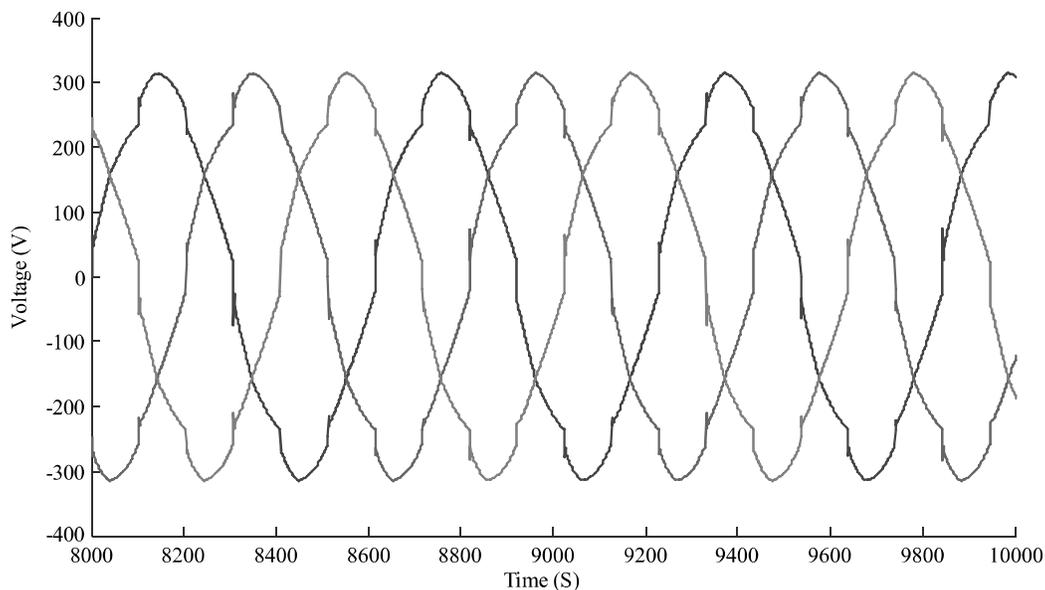


FIG. 4. SOURCE VOLTAGE WAVE FORMS OF SIMULATED MODEL

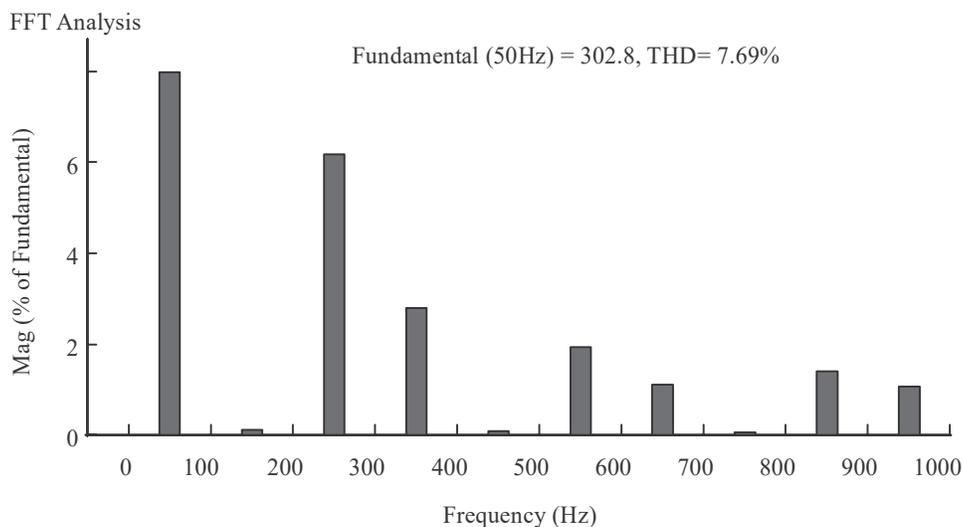


FIG. 5. HARMONIC SPECTRUM FOR SOURCE VOLTAGE OF SIMULATED MODEL

Proposed filter controlled through hysteresis control technique is simulated to confirm its effectiveness for harmonic mitigation of the system analyzed. Voltage waveforms shown in Fig. 7(a) shows improvement as almost sinusoidal waveforms are observed. On the other hand current waveforms shown in Fig. 7(b) have improved tremendously. Harmonic spectrums shown in Fig. 8(a-b) confirm the improvement as both THD values for current and voltage are less than 5%. Table 2 compares percentage THD values for current and voltage of selected model with and without proposed HAPF. Comparing Fig. 3 with Fig. 8(a) it is observed that all harmonics have reduced significantly for current. Same is observed for voltage from Fig. 5 and Fig. 8(b).

TABLE 1. PROPOSED HAPF PARAMETERS

Harmonic Order	Resistance ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )	Inductance (mH)
5	1.52	8.4	8.7
7	1.72	5.3	39
11	0.869	6.2	13.5
Higher	218	3.35	17.8

HAPF is designed for  $8\Omega$  load and shows desired harmonic mitigation. Simulation is performed by varying load resistance for 2, 4 and  $6\Omega$  to observe harmonics and effects of proposed HAPF considering  $8\Omega$  as maximum load.

Table 3 gives comparison of current and voltage THDs with and without proposed HAPF under different load condition it is observed that current harmonics increase as load resistance is increased whereas voltage THD is reduced. In both cases proposed HAPF mitigates harmonics successfully for considered load resistances.

## 5. CONCLUSIONS

Increase in nonlinear loads and power electronic converters have harmonically distorted voltage and currents in modern power systems. Adjustable speed drives are one of the common sources for injecting harmonically distorted currents in power system resulting in voltage harmonics. Harmonics in supply voltage degrades quality of power supplied to other equipment and may result in improper operation of equipment or damage. Hybrid filter technique combines the benefits of active and passive filters and

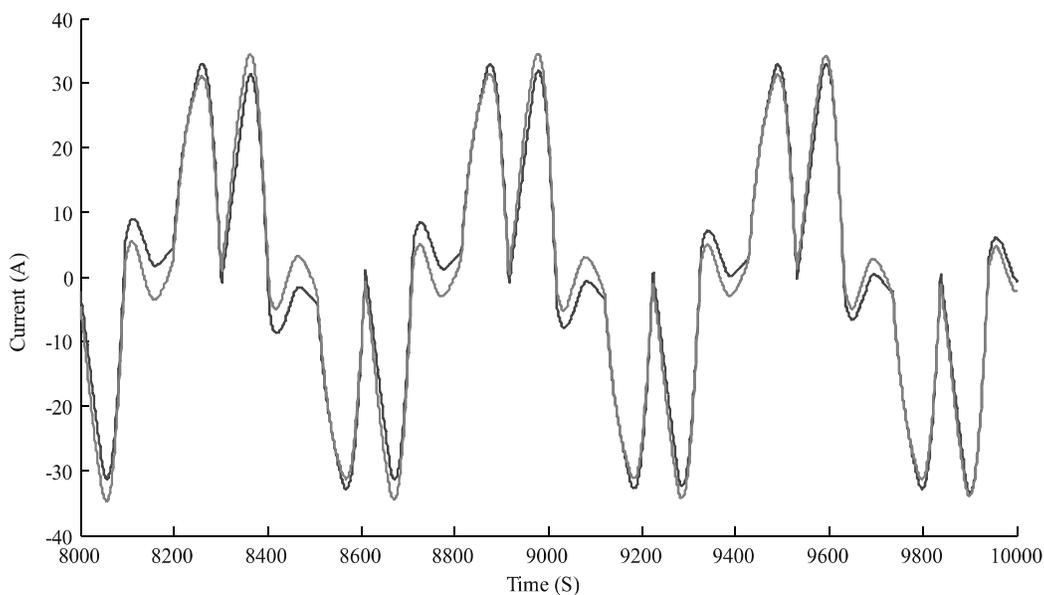


FIG. 6. HAPF CURRENT TRACKS THE REFERENCE CURRENT EXACTLY

proves to be superior solution to damaging problem of harmonics in power system.

In this research work, simulation analyses are performed on a section of power system consisting of a three phase AC source supplying a resistive load through a six pulse bridge rectifier. Simulation analysis show THD values of 18.91 and 7.69% for supply current and voltage respectively, both being greater than acceptable value of 5% given in IEEE standard 519. With the aid of P-Q theorem in static frames parameters of the HAPF are

selected to exactly track harmonic currents. Hysteresis control is employed for proposed filter. Simulation results after connecting the proposed filter confirms its efficacy as THD values for both voltage and current have reduced to 1.36 and 3.49% respectively. Simulation analysis for load resistance from 2 to 8Ω are performed to observe successful harmonic mitigation through proposed HAPF. It is therefore concluded that designed HAPF successfully tracks and mitigate the harmonic distortion caused by the selected nonlinear model for adjustable speed drive.

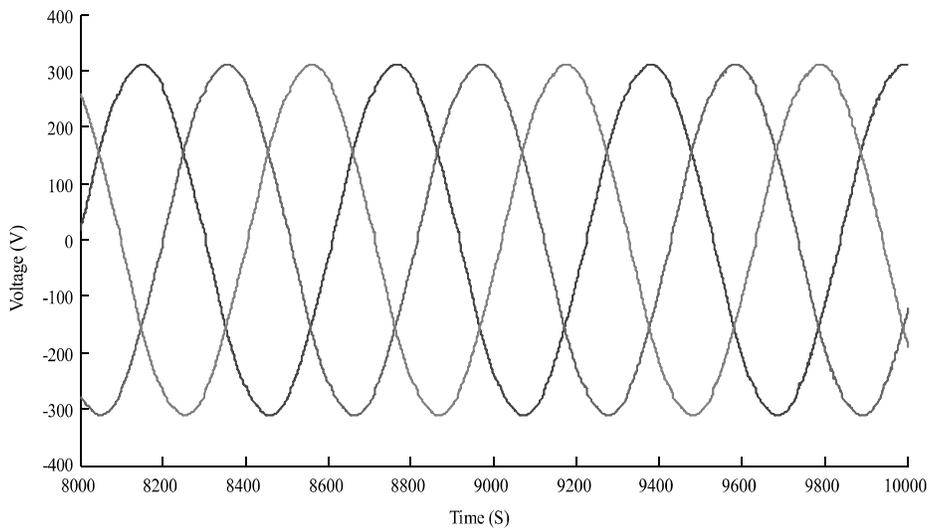


FIG. 7(a). WAVEFORMS OF SUPPLY VOLTAGES AFTER USING HAPF

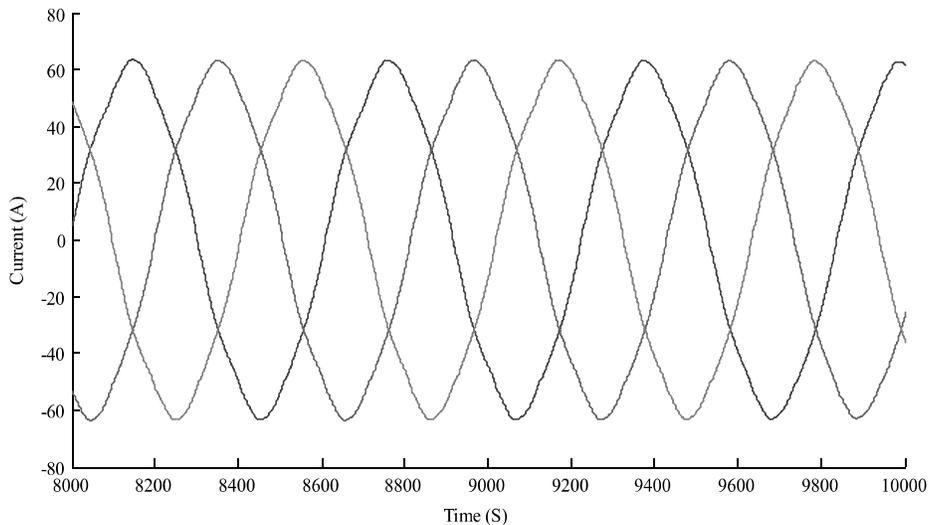


FIG. 7(b). WAVEFORMS OF SUPPLY CURRENTS AFTER USING HAPF

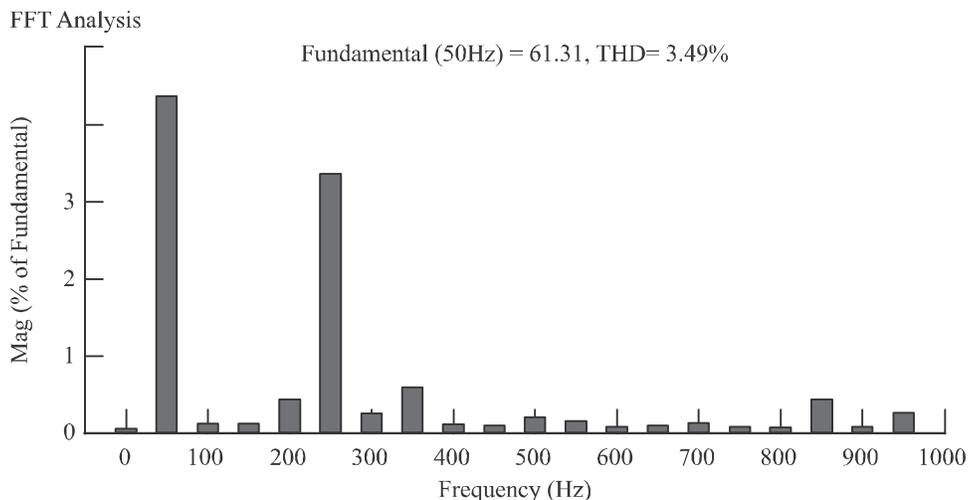


FIG. 8(a). HARMONIC SPECTRUM OF SUPPLY CURRENT AFTER USING HAPF FILTERING

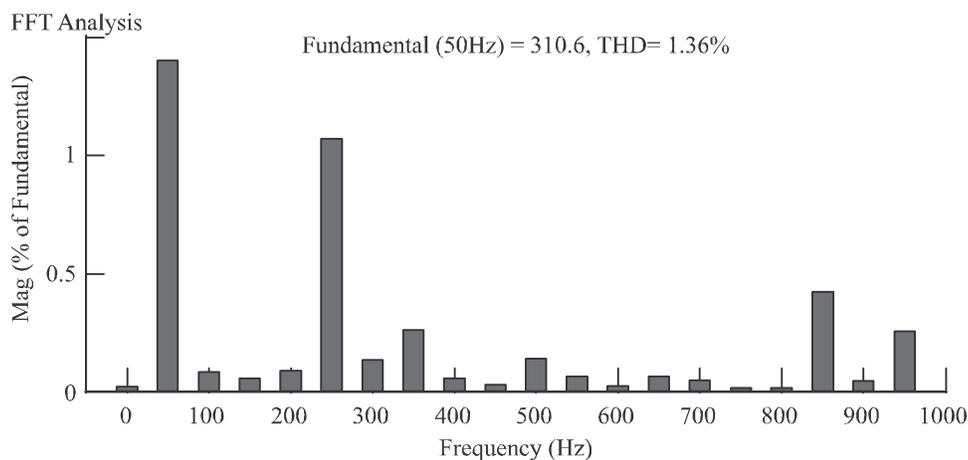


FIG. 8(b). HARMONIC SPECTRUM OF SUPPLY VOLTAGE AFTER USING HAPF

TABLE 2. COMPARISON OF VOLTAGE AND CURRENT %THD FOR SIMULATED MODEL

	THD (%)	
	Before HAPF	After HAPF
Voltage	7.69	1.36
Current	18.91	3.49

TABLE 3. COMPARISON OF VOLTAGE AND CURRENT %THD FOR SIMULATED MODEL FOR DIFFERENT LOAD RESISTANCE

Load Resistance (Ohms)	Voltage THD (%)		Current THD (%)	
	Before	After	Before	After
2	8.99	2.01	6.18	1.24
4	8.62	1.75	12.14	2.11
6	8.69	1.47	16.39	2.54
8	7.69	1.22	18.91	3.49

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